Research Article

Hayley L. Mickleburgh*, Liv Nilsson Stutz, Harry Fokkens

Virtual Archaeology of Death and Burial: A Procedure for Integrating 3D Visualization and Analysis in Archaeothanatology

https://doi.org/10.1515/opar-2020-0152
received January 06, 2021; accepted June 11, 2021

Abstract: The reconstruction of past mortuary rituals and practices increasingly incorporates analysis of the taphonomic history of the grave and buried body, using the framework provided by archaeothanatology. Archaeothanatological analysis relies on interpretation of the three-dimensional (3D) relationship of bones within the grave and traditionally depends on elaborate written descriptions and two-dimensional (2D) images of the remains during excavation to capture this spatial information. With the rapid development of inexpensive 3D tools, digital replicas (3D models) are now commonly available to preserve 3D information on human burials during excavation. A procedure developed using a test case to enhance archaeothanatological analysis and improve post-excavation analysis of human burials is described. Beyond preservation of static spatial information, 3D visualization techniques can be used in archaeothanatology to reconstruct the spatial displacement of bones over time, from deposition of the body to excavation of the skeletonized remains. The purpose of the procedure is to produce 3D simulations to visualize and test archaeothanatological hypotheses, thereby augmenting traditional archaeothanatological analysis. We illustrate our approach with the reconstruction of mortuary practices and burial taphonomy of a Bell Beaker burial from the site of Oostwoud-Tuithoorn, West-Frisia, the Netherlands. This case study was selected as the test case because of its relatively complete context information. The test case shows the potential for application of the procedure to older 2D field documentation, even when the amount and detail of documentation is less than ideal.

Keywords: archaeothanatology, burial taphonomy, mortuary archaeology, 3D visualization, photogrammetry

1 Introduction

Careful consideration of the effects of taphonomic processes within the grave is important for interpreting treatment of the body and understanding mortuary ritual in the past. An increasingly used framework to reconstruct the taphonomy of the grave, archaeothanatology, uses taphonomic principles and knowledge

Article note: This article is a part of the Special Issue on Art, Creativity and Automation. Sharing 3D Visualization Practices in Archaeology, edited by Loes Opgenhaffen, Martina Revello Lami, Hayley Mickleburgh.

*** Corresponding author: Hayley L. Mickleburgh,** Department of Cultural Sciences, Linnaeus University, Pelarhuset 7, Växjö 35252, Sweden, e-mail: hayley.mickleburgh@lnu.se
Liv Nilsson Stutz: Department of Cultural Sciences, Linnaeus University, Pelarhuset 7, Växjö 35252, Sweden
Harry Fokkens: Faculty of Archaeology, Leiden University, Leiden, The Netherlands
ORCID: Hayley L. Mickleburgh 0000-0001-9326-8097

of human anatomy and decomposition processes to interpret the spatial configuration of bones in a deposit. Archaeothanatology assumes that the configuration in which the bones are discovered is the product of the original position and the condition that the body was placed in, along with the shape, dimensions and material characteristics of the burial environment, taphonomic processes and human actions during mortuary treatment. For example, the precise position of and spatial relationships between the bones are used to infer whether the burial is a primary or secondary deposit, to distinguish collective burials (accumulated over time) from multiple burials (simultaneous deposition), to reveal whether the body was originally placed in a (perishable) container, to determine the stage of decomposition of the body upon burial (e.g. fresh and mummified), to identify postmortem and postdepositional manipulation of the body and grave (e.g. intentional removal of bodies/body parts) and to establish whether the burial occurred immediately after death or was delayed (Castex & Blaizot, 2017; Duday & Guillon, 2006; Duday, 2009; Harris & Tayles, 2012; Knüsel, 2014; Maureille & Sellier, 1996; Nelson, 1998; Ortiz, Chambon, & Molist, 2013).

Archaeothanatological principles are applied during excavation to analyse in detail the position and anatomical relation of the bones (i.e. are the bones articulated at the joints or not). Bones found out of their anatomical relation are carefully examined, and the direction and distance of bone displacement are recorded. Bone position is traditionally recorded in two-dimensional (2D) drawings and photographs of the burial, along with extensive textual descriptions of the position and rotation of each individual bone, and depth point measurements are also recorded. These descriptions form the basis for the interpretation of taphonomic processes and mortuary practices that shaped the burial feature as well as for the interpretation of contextual information and wider social meaning. Archaeothanatology has often been described as a field method (originally even termed "*anthropologie de terrain*" or "field anthropology"), and it is argued that the complex process of interpreting the spatial relationships between bones should be conducted during excavation of the burial (Duday, 2006; Duday, Courtaud, Crubezy, Sellier, & Tiller, 1990). The reasoning is that essential information on the precise *in situ* position and orientation of each individual bone and its relation to other bones and structures of the grave is only partially available after excavation. Duday (2006, p. 30) emphasizes the importance of conducting archaeothanatology in the field, in order to intricately describe bone positions and capture anatomical details, and states that "[*i*]*t is rarely possible to reconstitute this information afterwards if it is not noted in the field, no matter what the quality and abundance of the excavation archives*." Nonetheless, various studies of mortuary practices from different spatiotemporal contexts have demonstrated that their principles can be successfully applied post-excavation, using photographs, drawings and field notes (Aspöck, 2018; Green, 2018; Harris & Tayles, 2012; Nilsson Stutz, 2003, 2006; Peyroteo Stjerna, 2016; Tõrv, 2016; Willis & Tayles, 2009). While post-excavation archaeothanatology is necessarily reliant on the quality of field documentation, and while applying a methodology that relies on three-dimensional (3D) observations in the field situation to conventional 2D documentation has its limits, its systemic application can still yield previously unknown information.

Whether applied in the field or after excavation, archaeothanatological analysis always relies on the ability to infer and interpret 3D information about the configuration of bones in the grave. This 3D information is relayed through extensive textual descriptions; descriptions that integrate at once the description of the bone positions and the reconstruction of taphonomic processes and mortuary practices that shaped the burial feature (Duday, 2006, 2009). With the rapid development of (affordable) tools to capture 3D information in the field, 3D models (i.e. digital replicas) have become a viable way to preserve information on the position of bones. Studies focused on mortuary analysis have demonstrated that using 3D models of *in situ* human remains, particularly when captured during multiple phases of excavation and integrated into site-wide 3D GIS analysis, can greatly improve interpretation of burial taphonomy and allow us to better understand mortuary practices in the past (Berggren et al., 2015; Haddow, Sadvari, Knüsel, & Hadad, 2016; Knüsel, Haddow, Sadvari, Dell'Unto, & Forte, 2013; Ulguim, 2017; Wilhelmson & Dell'Unto, 2015). This use of 3D models furthermore greatly improves the potential of post-excavation archaeothanatology as well as the ability to conduct replication studies or revisit earlier archaeothanatological interpretations. However, digital replicas produced through 3D photogrammetry still have some limitations with regards to the information they capture on the spatial relation of bones and objects in a grave. 3D digital replicas of burials, in essence, provide a "snapshot" topology of the excavation surface at a specific stage during excavation of the remains, and are often lacking a large part of the spatial relations between, as well as the volumetric information on bones, grave goods and grave structures. Even when multiple phases of excavation are documented, some information on spatial relations will be lost unless the 3D volume and position of each bone and object within the grave can be reconstructed.

In this article, we describe the method of 3D documentation and analysis that we used to study the spatial relation between individual bones in a burial deposit. The purpose of the protocol we followed is to preserve and reconstruct 3D information related to the spatial displacement of bones over time due to burial taphonomy and also to produce animated 3D simulations to visualize and test taphonomic hypotheses. The method provides highly detailed information on the spatial relation of human remains and other objects within the burial environment and has significant applications in both the study of past mortuary practices in archaeology as well as model and method development in archaeothanatology. We show how it can be used to reconstruct 3D information from older 2D excavation documentation, to aid post-excavation archaeothanatological analysis, even when the amount and detail of field documentation is less than ideal. We illustrate our approach with the reconstruction of mortuary practices and burial taphonomy of a Bell Beaker burial from the site of Oostwoud-Tuithoorn, West-Frisia, the Netherlands.

2 Description of the Case Study and Post-Excavation Archaeothanatological Analysis

As a part of a wider project reanalysing old excavation data and material from the Late Neolithic/Early Bronze Age (2500–1700 BC) site of Oostwoud-Tuithoorn, West-Frisia, the Netherlands (2500–1700 BC), we conducted a post-excavation archaeothanatological investigation of the burial of a male aged 26–35 years at death (burial 228). Oostwoud-Tuithoorn consisted of two low burial mounds on and in arable land. Most of the burials consisted of shallow pits dug into low mounds. Excavations by Van Giffen in the 1950s (Figures 1 and 2) and De Weerd in the early 1960s resulted in a very detailed archive of field documentation, although little was published about the site at that time. The skeletons had been the subject of earlier research, but scientific and technological advances in the past 40 years prompted a series of new analyses, including osteological, stable isotope and ancient DNA analysis, the results of which emphasize the significance of this site in furthering our understanding of Bell Beaker mobility and genetics (Fokkens, Veselka, Bourgeois,

Figure 1: Aerial photo of the 1956 excavations of the two burial mounds at Oostwoud-Tuithoorn, led by Van Giffen. Burial 228 can be observed in the top centre (black arrow).

Olalde, & Reich, 2017; Olalde et al., 2018). Burial mound I contained skeletons in the extended supine position (considered typical for the Bronze Age). Burial mound II contained skeletons in the flexed position on the side, which is considered typical for the Late Neolithic. The typical body position for Late Neolithic males was flexed on the left side, with body oriented east–west, and with the face directed to the south. Females were placed flexed on the right side with the body oriented either east–west (with the face directed to the north) or north–south (with the face directed to the west). In some of the burials, missing and displaced body parts have been noted. Poor preservation was ruled out as the cause for these missing elements, since overall preservation of all skeletal elements at the site is very good, and bones that are known to be more susceptible to degradation are not overrepresented among the missing elements. While loss during excavation could have contributed, the absence of some bones has raised the question whether secondary treatment of the human remains was practiced or whether human disturbance (e.g. ploughing of the site not long after burial) could have been the cause (Fokkens et al., 2017). To better understand mortuary treatment in this Late Neolithic/Early Bronze Age community, we created a virtual reconstruction of the spatial relation of the bones in burial 228. Individual 228 was found in mound II, and the skeleton was well preserved.

Based on the available photographs taken during excavation of burial 228 in 1956, the remains appeared to be in partly supine position, and partly turned to the left side, with the body oriented east–west, the head rotated to the left, and the lower limbs, which were moderately flexed at the hip and knee, rotated to the left. Overall, the skeleton is well articulated, suggesting that this is a primary burial (Figures 2 and 3). Based on the fact that there is no movement of bones outside of the estimated initial space of the cadaver that can be linked to the natural decomposition process, the body decomposed in a filled space. Postdepositional interferences appear to have affected this burial, some of which most likely occurred during excavation. Six disarticulated rib fragments and the first right metacarpal are depicted situated to the left of the lower vertebral column, probably as a result of temporary placement in this area by excavators, as small elements like these easily become displaced during excavation and are often collected close

Figure 2: Selection of photographs taken of burial 228 during excavation.

Figure 3: Burial 228 during excavation in 1956.

to their original location. Other movements, including those of the right upper limb and shoulder girdle, and both lower limbs, took place when parts of the skeleton were still at least partially articulated and therefore must have occurred within a few years of the burial. Among these movements is the most striking feature of burial 228: the fact that the articulated distal fragments of the right ulna and radius, and the right carpals and metacarpals, were found by the feet of the skeleton, together with the manubrium. The fracture surfaces of the distal right ulna and radius, which were examined by the primary author, suggest recent damage, which probably occurred during excavation. This is supported by a photograph taken during excavation (Figure 4), showing the sharp cut of a shovel in the soil and the fragmented ends of the radius

Figure 4: Fragmented distal right radius and ulna, and shovel cut.

and ulna. The right clavicle, scapula, humerus and proximal parts of the right ulna and radius were missing. It is not possible to ascertain with certainty whether these elements were present during excavation, but it is possible that the day-labourers who first found this burial, and accidentally cut the radius and ulna with a shovel, failed to retrieve these elements. The fact that the right hand was found mostly in anatomical articulation, combined with the recent damage to the radius and ulna, suggests that the entire right upper limb (or a large portion of it) was positioned by the feet of the individual. This raises the question whether the limb was removed shortly after death when the body was still completely fleshed or once the connective tissues had (partly) decomposed. Based on examination by the primary author, there were no signs of cutmarks consistent with de-fleshing or manual disarticulation on the bones.

The left shoulder girdle (i.e. the scapula and clavicle) was strongly projected upward and supported laterally by the wall of the grave. The left arm was in abduction and the forearm flexed and in pronation, with the left hand resting in front of the chest. The sternum was found superior, and to the right of its anatomical position, and surrounded by the ribs of the right hemi-thorax. It is likely that the movement of the sternum occurred when the ribcage had already (partially) flattened due to natural decomposition processes, as displacement of the sternum while the ribcage retained its original volume would have created space into which the metacarpals of the left hand could have moved once the ribcage and left hand eventually skeletonized completely (which is not the case: the left metacarpals were found in articulation).

Other major disturbances in the skeleton are apparent in the pelvic girdle and lower limbs. The pelvis is fragmented and difficult to observe in detail. The bones of the lower right limb are partially fragmented. The right femur is fractured, and the proximal end is missing; the right fibula is fractured in half, and the distal right tibia is missing. The right foot is relatively well articulated. The lower left limb shows similar disturbances, although the left femur is articulated with the fragmented pelvis, the left tibia is disarticulated from the femur, fibula and foot, and has rotated laterally, presenting its posterior side. The left fibula is disarticulated, laterally displaced and rotated, thus presenting the posterior surface. Some of the bones of the left foot are present, but they appear scattered and are difficult to observe in detail.

The major disarticulations, fragmentation and displacements of bones can be linked to postdepositional interference/disturbance. This must have taken place when the skeleton was only partially disarticulated, as some joints appear to have been very well preserved, in particular those of the right forearm and hand, which have been moved over a meter without disarticulation, as well as the left forearm and hand. Other bones, like the right scapula and clavicle, were loose enough at the time of disturbance to detach completely, but only after having affected other bones in the vicinity (in particular, the sternum that seems to have been dragged to the right, which is the opposite direction of the expected movement resulting from natural decomposition in a body slightly rotated to the left). Other slight movements and disarticulations can be attributed to the natural decomposition process in a subsurface environment, such as the upward projection of the left shoulder and the downward displacement of the skull, which occur naturally as the body slumps downward in the grave during decay of the soft tissues.

The displacement and damage to different elements of the skeleton suggest that they occurred at a single point in time during decomposition, affecting the elevated portions of the body in a linear configuration. These observations provide us with a hypothesis for the events that led to the final position of the bones of burial 228. Considering the ubiquitous presence and the directionality of prehistoric plough marks around the burials at Oostwoud-Tuithoorn, the observed bone displacements may have resulted from ploughing of the area within a few years of the burial of this individual. This hypothesis was already tentatively put forward in an earlier analysis of the burial and its surroundings (Fokkens et al., 2017).

3 Methods

The use of 3D tools to examine human burials has been demonstrated to assist and improve mortuary analysis and understanding of mortuary practices in the past (Berggren et al., 2015; Haddow et al., 2016;

Knüsel et al., 2013; Ulguim, 2017; Wilhelmson & Dell'Unto, 2015). The protocol described here augments the archaeothanatological reconstruction of burial taphonomy and mortuary practices in archaeological burials. The aim is to enable both visualization of the 3D relation between the bones in the deposit (3D reconstruction) and examination of potential bone movement trajectories and sequences (3D simulation). The protocol can be adapted depending on the amount/quality of field documentation available, while using the same basic set of 3D digital tools. Some of these are now commonly used in (commercial) archaeology, such as 3D photogrammetry (SfM-MVS), while others are less commonly applied or tend to be applied in selected (public outreach-oriented) visualizations, such as 3D animation. The tools, the software packages and the parameters we used in this study are described in this section.

3D models of the individual bones of the excavated skeleton are created using 3D photogrammetry as described in Section 2. Photographs taken and drawings made during excavation of the burial are then imported as reference images and for camera mapping in a 3D modelling, 3D animation and rendering application (we used Maxon's Cinema 4D R23) to position the 3D bone models in the spatial relation and configuration observed during excavation. This provides a digital 3D reconstruction of the burial feature in its final position "B." To estimate the initial "A" position of the freshly buried body (i.e. with the bones in anatomical relation), we conducted post-excavation archaeothanatological analysis, which indicated that the body was placed in fresh, anatomically intact condition as a primary burial in the grave, on the left side (see Section 2). Subsequently, we then used a rigged (i.e. animatable) anatomical reference model of an adult male human skeleton with soft tissue body volume developed by Motioncow (Figure 5) to replicate the original body position on burial. Since the upper right limb was not in the anatomical position during excavation, its original position upon interment was assumed based on the position observed in other burials at the site as well as Bell Beaker burials known from other sites in northwest Europe. While its precise original position cannot be known, the position of the rest of the remains (lying on the left side) indicates that it would have been slightly elevated in the grave in relation to the thorax (see Section 2). The presence of the first right metacarpal in the abdomen area is suggestive of the right limb being originally placed as indicated in Figure 5; however, as explained above, this element appears to have been displaced during excavation, and its original position in the grave was not documented. The anatomical reference model is scaled to the estimated height of the individual and posed in the estimated body position (this position can be adapted during the analysis process to test hypotheses). Using the reference model as a guide, the 3D animation features of the Cinema 4D software are used to visualize the potential movements of body parts and bones during the processes of decomposition, and (if applicable) disturbance and re-deposition of the body and bones. Individual animation of the digital bone replicas from position A to

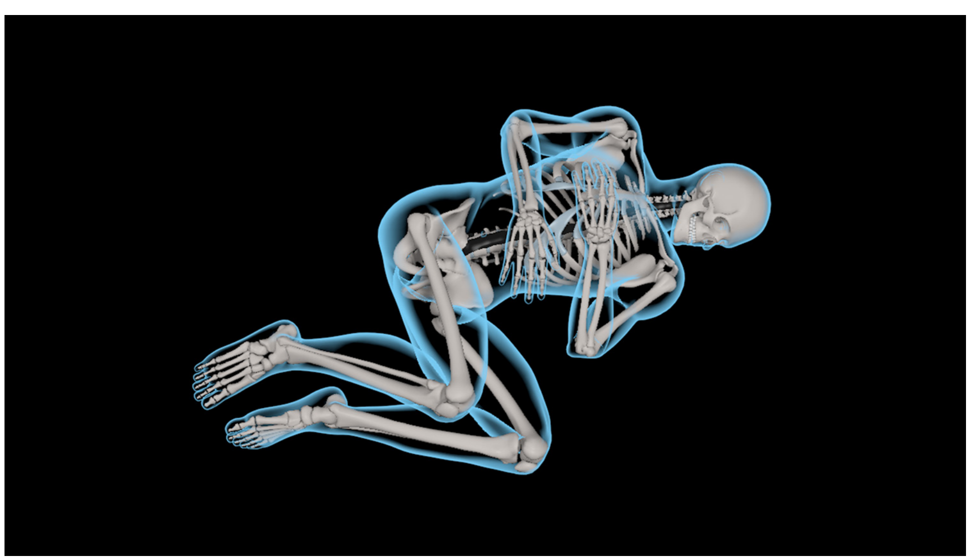

Figure 5: Motioncow digital anatomical reference model (posed).

position B permits continual inspection of the spatial relation of the bones and allows us to identify the sequence and trajectories (motion paths) of possible movements (i.e. examine physically possible motion paths, without bones colliding and passing through each other).

3.1 Documentation

The creation of virtual reconstructions and simulations is a scientific process, which relies on the systematic and rigorous collection and cross-referencing of numerous data sources and the methods used to interpret these sources and test hypotheses (Ferdani, Demetrescu, Cavalieri, Pace, & Lenzi, 2020). The necessity to develop and implement guidelines and best practices for 3D visualization, together with a host of other digital practices, was first formally recognized with the creation of the London Charter (Beacham, Denard, & Niccolucci, 2006). The emphasis in this and other charters that followed (e.g. the Seville Principles) was on the importance of transparency in the creation of 3D reconstructions and visualizations as well as sustainable curation of the resulting digital data. Researchers working on virtual reconstructions in archaeology sought ways to maintain transparency, arguing that the "scientific processes behind an archaeological virtual reconstruction" (Demetrescu & Fanini, 2017, p. 500) should be documented and developed frameworks to do so. For the study of architectural structures and site contexts, archaeologists increasingly use the Extended Matrix, a formal language for the documentation of virtual reconstruction for the purpose of transparency and completeness of the scientific process (Demetrescu, 2015, 2017). The Extended Matrix is based on the stratigraphic approach to the recording and managing of archaeological data and extends that approach and its elements (stratigraphic unit, activity and Harris matrix) to 3D virtual reconstruction. While these principles can be applied to the spatial features of a human burial context to a certain extent, i.e. regarding its stratigraphic relation to other features of an archaeological site, they cannot be applied to the (super)position of individual bones, which is determined by the anatomical relation of the bones in the human body and the position in which the body is originally deposited, and to the process of decomposition of the soft tissues of the body. Recognizing the importance of documenting the virtual reconstruction process and produced metadata (see also Ulguim, 2017), in this study, we decided to use the annotation function within Cinema 4D, including information on measurements of 3D models and real-world objects depicted in the 2D images, and on the process of determining the motion paths of each individual bone during simulation. The latter included information on motion paths (defined by direction and speed of movement), which led to collisions of bones in 3D space (both physically possible and impossible). Animation settings (e.g. keyframe timing and movement sequence) of each step in the process of testing motion paths were also recorded.

3.2 3D Photogrammetry (SfM-MVS)

The skeletal remains recovered from burial 228 are currently kept at the province of North-Holland's depot for Archaeology (*Provinciaal depot voor archeologie Noord-Holland*) in Castricum, the Netherlands. These remains were studied by the primary author in December 2019, and 3D models were created using photogrammetry. Despite good preservation of the skeleton of burial 228 overall, some parts were fragmented. The fragmented ribs and the vertebrae were not 3D modelled, due to the fact that the thorax area showed no signs of disturbance or movement that is not consistent with natural decomposition processes, and creating digital replicas of the fragments of the ribs and the vertebrae would have been immensely time consuming. Similarly, the (meta)carpals, (meta)tarsals and phalanges of the hands and feet were not documented, since these were largely found in anatomical relation, and those that were not, are difficult to observe in detail on the photographs. Digital replicas were created of the cranium, long bones and long bone fragments, the sternum body and manubrium as well as the remaining pelvic fragments.

In order to generate digital replicas of the individual bones of the skeleton, we used the image-based modelling technique 3D photogrammetry (SfM-MVS), in which 3D data are computed based on a series of 2D images of an object. This method was selected due to the relatively low cost of required software and hardware. This method is also rapidly becoming a standard tool in archaeological documentation (De Reu et al., 2014; Sapirstein & Murray, 2017).

Overlapping digital photographs were taken using a Leica D-LUX5 10.1 MP compact digital camera. A fixed focal length was used (35 mm), and the aperture value was set to f8.0. Bones were photographed broadly following the turntable method described in the study by Porter, Roussel and Soressi (2016), using a total of eight tiers (at approx. 10°, 30°, 50° and 70° angles) at intervals of 30° (bottom to top tier) with four on each side of the bone.[1] Agisoft Metashape Professional 1.5 software was used to process 2D images and produce 3D models. Sparse point clouds were generated, and gradual selection filtering and optimization were performed to remove outliers. Images were aligned, and subsequently, dense point clouds were built at high resolution. The accuracy of all models indicated an average error of ~1.5 mm. Meshes and textures were generated at both low and high resolution for all models. Meshes were scaled using a scale present in photographs of the bones, and lower-resolution models were exported as .obj for use in 3D animation software Cinema 4D (see Section 2). While high-resolution models could be exported and used, the use of lower-resolution models avoids slowing down the viewport during the process of animation as well as during the rendering of images in Cinema 4D.

3.3 Camera Mapping and 3D Animation

The digital replicas (3D models of each bone in .obj file format) were imported into Maxon's Cinema 4D R23.008. Cinema 4D is a very powerful 3D modelling, 3D animation and rendering application. This software allows the user to create or import 3D objects, which can be textured, lighted and animated using an extensive set of tools. Cinema 4D is broadly appealing for its relative speed and ease of use, and for the fact that it is closely integrated with Adobe After Effects and Premiere Pro, making it a favoured software by motion graphics designers and animators producing animated artwork for web, television or film. While we used Cinema 4D during development of the pipeline, open-source 3D creation software such as Blender can easily be substituted.

When importing the 3D models into Cinema 4D, it is important to ensure that each model retains the same relative size. Cinema 4D uses real-world metric measurement units. As we scaled the meshes using a scale present in photographs of the bones prior to exporting the .obj files from Agisoft Metashape, the models could be imported into Cinema 4D in the same relative real-world sizes.

Burial 228 was photographed from various angles during its excavation in 1956 (Figure 2), and these images depict objects and structures with known real-world measurements and perpendicular straight lines, such as the excavation units and the bones of the skeleton. These images could therefore be used as references to position the 3D bone models in their original spatial configuration. In order to do this, we used a method known as camera mapping or projection mapping, which allows 2D images to be projected over low polygon 3D geometry. Camera mapping is a powerful technique that is commonly used by visual effects studios. Once the images are projected, this technique allows the user to move around the textured 3D scene. Depending on the coverage of the 3D model by available projected photos, the entire scene can be fully textured and can allow creation of an animated scene "walk through." In our case, the objective is not

1 The number of images taken of the individual bones is higher than the number needed to generate 3D models of sufficient resolution for the purposes of the protocol described in this article. The large number of images was collected in order to generate 3D models of very high resolution for the purposes of a separate study. Reducing the number of images captured would save a considerable amount of time both during image capture and processing.

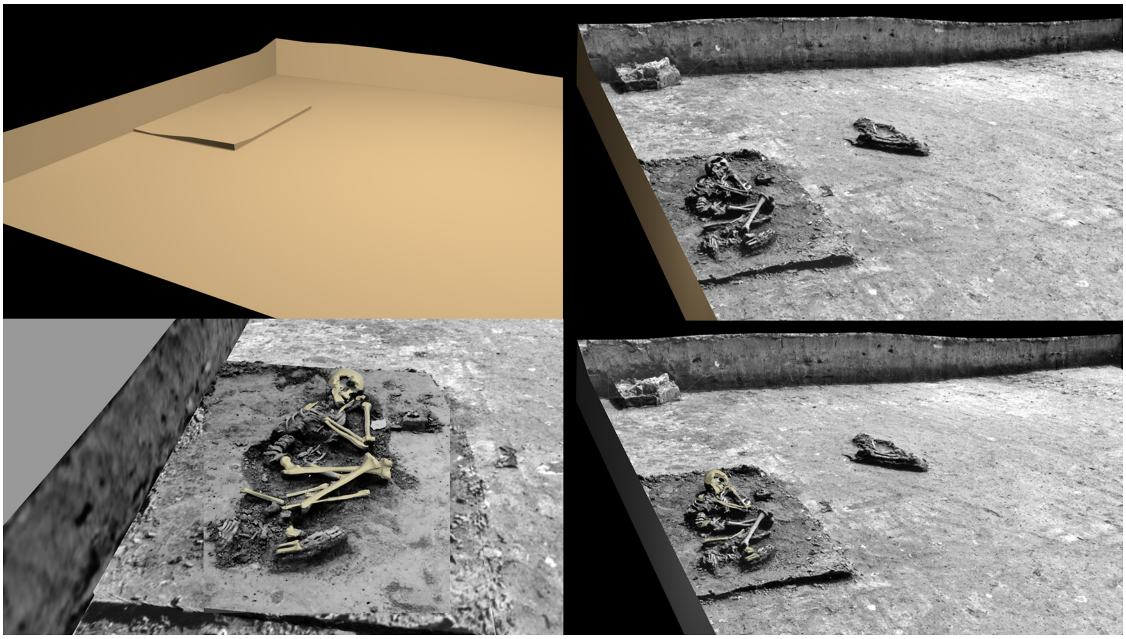

Figure 6: Top left: low polygon model of the excavation unit created in Cinema 4D. Top right: projection of image on 3D model, once correct position and perspective of camera have been obtained. Bottom right: placing the digital replicas of the bones in position from this particular projection camera. Bottom left: placing the digital replicas of the bones in position by using another image/angle in the projection camera.

the recreation of the entire scene, but the creation of projections from different angles in order to position the bones, meaning full coverage is not necessary.

We created low polygon meshes of portions of the depicted excavation units, including the unit plan and profiles, and the elevated portion on which the skeleton of burial 228 was positioned, based on measurements taken from the field documentation (profile drawings and plan drawings). Individual images of the excavation unit and burial 228 during excavation were imported into Cinema 4D and placed on a background object behind the 3D model of the excavation unit. The 3D model was subsequently rotated and positioned using the perspective, known measurements and perpendicular straight lines visible in the reference image, to match the orientation shown in the image. A camera object was used to view the 3D model in position. Camera objects in Cinema 4D, and similar software packages, include a large number of settings that can be manipulated. Since no information was available on the type of camera and camera settings used for the original photographs taken in 1956, testing of different focal depth settings was necessary to match the perspective of the 2D images. Once the correct camera position and perspective is obtained, the 2D images can be projected onto the 3D model. When viewing the projected scene through the camera object, which now has the correct perspective, the 3D models of the bones can be positioned. Positions are established using the projections from different angles, resulting in the final position B of the skeleton (Figure 6).

Once the bone positions A (see description above) and B had been established,[2] bone movements were animated by setting keyframes on the animation timeline for each 3D bone model at certain positions.

2 Anchor points between positions A and B comprised the general position of the left femur (which would have been in a relatively stable, supported position in the grave and showed only slight lateral rotation) as well as the position of the ribcage as uncovered in 1956. The flattening of the ribcage as a result of decomposition of the soft tissues is well documented in archaeothanatology, and the relation between the original position and volume of the ribcage and its position after flattening is well understood. While the ribs are not visible in the 3D reconstruction, the ribcage of the Motioncow model and the position of the flattened ribs and the left femur in the photographs could be used as anchor points to tie in the reconstructed positions A and B.

Cinema 4D will calculate the shortest movement trajectory between two positions, which in some cases may lead to collisions of bones in space. The movement of each individual bone between position A and B (motion paths) was examined individually and in conjunction with other movements, to examine physically possible motion paths, without bones colliding. This permits identification of the sequence and trajectories of all movements (i.e. specific duration, path and sequence).

4 Results: 3D Reconstruction and Simulation

Once positions A and B of each individual bone were established (Figure 7), movements were animated along the shortest possible motion path, which is calculated by the animation software. Movements were played simultaneously, allowing us to identify physically impossible motion paths, i.e. movements that would be impossible considering gravity or direction, or movements leading to intersecting of bones. The motion path of each 3D bone model was examined to establish how timing and speed of the movement affected the path and the paths of neighbouring bones. Motion paths were subsequently adjusted in speed, timing and direction/rotation to simulate physically possible movements. The timing of certain movements associated with the natural decomposition of the body and with the disturbance of the remains was already established based on post-excavation archaeothanatological analysis. For instance, the displacement of the

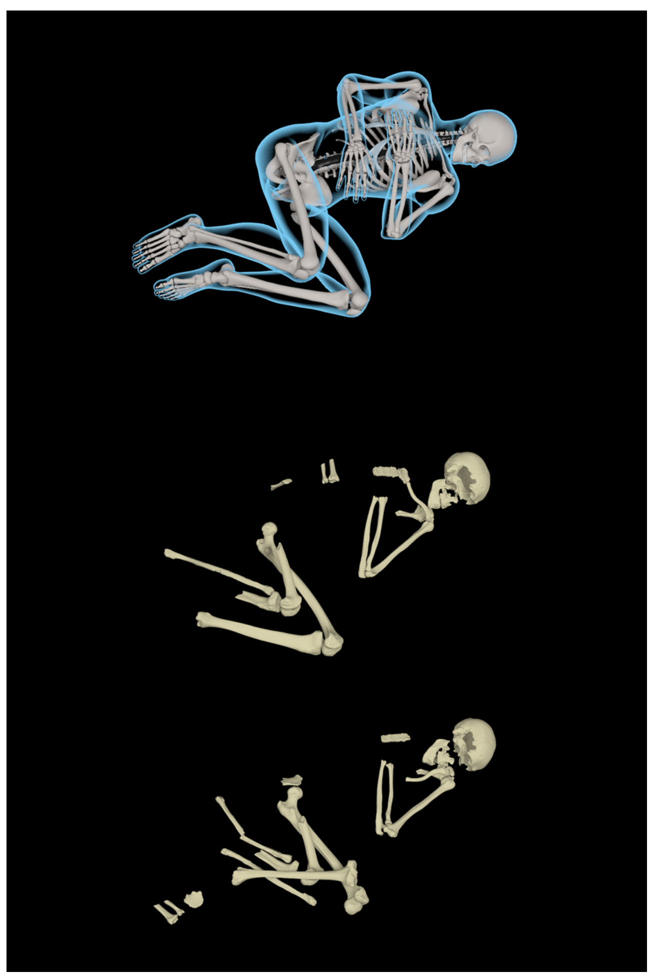

Figure 7: Top: posed Motioncow anatomical reference body. Middle: reconstructed position A of the skeleton. Bottom: reconstructed position B of the skeleton.

sternum body and the manubrium must have occurred when the thorax was partially decomposed and flattened, but when the carpals and metacarpals of the hands were still held in the articulated position with the upper limbs by connective tissue. The right hand ended up placed at the feet, with the carpals and metacarpals, as well as a couple of proximal phalanges, still in articulation. The left hand was resting on the thorax and still largely in articulation. The latter indicates that the upward and lateral movement of the sternum body and manubrium occurred after the thorax (and hence the upper left limb that was resting on it) had (partially) flattened and moved downward into the grave, since if this were not the case, the small bones of the left hand would have fallen (out of anatomical articulation) into the cavity created by the thorax when it flattened. The timing of bone movements was therefore adjusted to reflect this. In the case of the lower left limb, the shortest motion path calculated by Cinema 4D for the movement of the left tibia would be physically impossible, since the rotation is not consistent with the direction of bone displacement within the soil matrix. The rotation was adjusted accordingly. Position B of the left tibia, resting on the right distal femur and proximal tibia, indicates that the movement of the latter two bones downward in the grave must have occurred prior to the movement of the tibia. Simultaneous movement of these three bones during simulation – even with a range of adjusted speeds – led to intersection of the bones that would be physically impossible in the real world, confirming that the disturbance of the left tibia occurred after downward movement of the right lower limb due to decomposition. The timing of the motion paths of these bones was adjusted to reflect this. Further intersection occurred between the right distal femur and the left tibia, indicating that the slight medial rotation of the right femur and its final position on the left femur occurred as a result of the disturbance of the left tibia: the latter pushed the right femur into its final resting place. Simulation of movements also indicated that the displacement of the left tibia and left fibula must have occurred simultaneously, since analysis of the physically possible motion paths revealed that movement of either of the bones individually before the other led to intersection of the 3D bone models.

The full reconstruction of the spatial relation of the bones of burial 228 in both position A and position B, as well as the simulated bone movements discussed above, can be viewed in Video 1.[3] The animation visualizes the movement of the skull, upper left limb, left femur, right distal femur and proximal tibia moving downward into the grave, which occurs naturally during decomposition of the soft tissues and "settling" of the bones in the grave. The bones of the lower limbs, a fragment of the right ilium, the sternum body, the manubrium and the distal right ulna and radius (visualized in blue) are seen moving as a result of the disturbance of the burial. These movements occur after (at least partial) flattening of the ribcage, and after the (slight) downward displacement of the bones in the lower right limb, but before complete decay of the soft tissues.

The motion paths and sequence of these movements shown in the video are supported by the simulation of potential movements. In conjunction, these simulated motion paths support and strengthen the archaeothanatological analysis conducted using 2D images. Both the motion paths were reconstructed and the archaeothanatological analysis identified a single disturbing force, which led to the fracturing and displacement of elevated portions of the skeleton, and occurred in west–east direction. This disturbance is consistent in width and force with a simple and light scratch plough known to have been used in this period (Fokkens, 1998). The plough, moving in west to east direction, first disarticulated and scattered the bones of the right foot, then caught on the left tibia and fibula – moving them eastward – and impacted and fractured the distal right tibia, right fibula, proximal right femur and the pelvis. The missing portions of these bones may have been dragged to the surface and not reburied. The plough then likely caught the slightly elevated right shoulder and detached the entire right upper limb and the manubrium, which were still connected by soft tissue. This caused the sternum body to be moved (dragged) laterally and upward in the thorax. Although only the distal portions of the right ulna and radius and a portion of the right hand were found, it is likely that the entire upper right limb or arm was placed back into the soil intentionally together with the manubrium, as there is evidence that the fracture of the ulna and radius occurred during excavation. The disturbance of the grave must have occurred within a few months to a few years of burial of the freshly

3 The supplementary file is available at https://doi.org/10.1515/opar-2020-0152.

deceased body, since skeletonization is known to occur within this timeframe in shallow burials in clay-rich soils in temperate climates. A more precise estimation is difficult to make, since the season of burial and a range of intrinsic and extrinsic parameters would have influenced the rate of decomposition of the body. However, it is clear that the disturbance of the grave occurred within living memory, and the location of the burial and identity of the deceased individual were therefore more than likely known to the persons working the plough. Unintentional ploughing of the area known to contain human remains seems very unlikely, because the burial mound, although not very high, was a distinct and human-managed feature in the landscape. Plough marks pertaining to different phases of use of the area were identified during the excavations. These marks represent only the instances where the plough went deeper than it normally would, creating marks in the sterile subsoil. Under normal conditions, the shallow graves would not have been disturbed by the ploughing activities. Nonetheless, they are indicative of a longstanding use of the area for both burial of the dead and farming. In fact, at Oostwoud-Tuithoorn there are two more skeletons in the same burial mound that appear to have been affected by ploughing not too long after burial (Fokkens et al., 2017). Of one, the skull was found at some distance from the rest of the skeleton, and of the other, the lower half of the skeleton was displaced and redeposited around a meter away. Animal scavenging and burrowing is again unlikely in these cases, since the displaced elements were recovered at a similar depth to the original deposit, and there was no evidence of gnaw marks on the bones. In the last phase of use, the elevated mound was avoided entirely when ploughing, as evidenced by the plough marks running around it in the latest phase.

We argue that the dual use of the area, for agriculture and burial, together with indications that bodies disturbed by ploughing were intentionally redeposited into the earth, indicates that the practices of farming and mortuary ritual were not mutually exclusive, but can be understood as part of the spectrum of engagement with the landscape reflecting a worldview in which death and the afterlife were inseparable from daily life activities such as ploughing. The integration of burials and burial monuments (mounds) into the farming land, and *vice versa*, points to interwovenness of the realms of life and death.

5 Discussion and Conclusions

Next to providing an animated visualization of the archaeothanatological reconstruction, the simulation process helped strengthen the archaeothanatological reconstruction and interpretation of the natural decomposition process in a filled grave, which was followed by a single disturbance event imposing force on the elevated portions of the body in west to east direction, by allowing us to rule out certain motion paths and by confirming the simultaneous or sequential movement of individual bones during the disturbance. These features of 3D simulation can be of particular value in the study of highly complex disarticulated or commingled burial deposits, such as mass graves, and burials and tombs containing large amounts of highly fragmented remains. Another important advantage of the procedure we used is the fact that simulation can be repeated to test specific or alternative hypotheses. The 3D reconstructions allow for non-destructive and highly detailed (re)analysis of taphonomic data and the reconstruction of the sequence of disarticulation and movement of bones.

In exploring the potential of this procedure to assist in archaeothanatological analysis, we selected a case study that would present a challenge to the technical aspects of the procedure (i.e. working with older excavation data, with relatively few original images of the skeleton in site), but would not necessarily be considered a challenging case for archaeothanatological investigation. The latter helped us to evaluate the results of the technical procedure, since the archaeothanatological interpretation is well supported using traditional post-excavation archaeothanatological analysis. By testing the procedure to reconstruct 3D information from old 2D excavation data on a case with a relatively well-documented context and excavation history (e.g. including information on the skill and experience of the excavators [day-labourers] who first encountered burial 228), we hope to have demonstrated the potential of using this method to augment archaeothanatological analysis. In our case, the number of photographs was small, and field drawings of this particular grave during excavation were lacking. Despite this, an approximation could be made of the spatial configuration of the bones in the grave upon recovery in 1956. The procedure therefore opens up new opportunities to revisit existing datasets and extract more information from them, including new opportunities to study the taphonomic history of human burials that were not recorded in 3D. While our case study used 2D excavation data from the 1950s, the procedure can be suitable for use on more recently excavated burials, which were captured in 3D using photogrammetry during excavation. As discussed in Section 1, such 3D models provide only a single topological surface at one moment during excavation and, with the exception of some studies (Berggren et al., 2015; Knüsel et al., 2013; Ulguim, 2017; Wilhelmson & Dell'Unto, 2015), are often used only for visualization and presentation purposes in both commercial and academic archaeology. However, such models can help the precise positioning of digital bone replicas to establish the "B" position described above. The 3D reconstruction of burials in this way helps preserve the spatial relation and 3D volumes on which archaeothanatological methods and principles rely. Since such digital reconstructions can be easily shared, they can furthermore promote (re)analysis by other researchers. Future work will include examination of the accuracy and precision of the procedure in order to develop its potential for more routine application in mortuary analysis. This work will be conducted as a part of an ongoing programme of human decomposition experiments, led by the first author at the forensic taphonomy research facility at Texas State University, in which the decomposition, skeletonization, disarticulation and bone displacement over time are documented in 3D in a series of experiments using donated human cadavers (Mickleburgh, 2018; Mickleburgh & Wescott, 2018; Mickleburgh et al., in press). Since the original body position and all bone movements are documented in these experiments, they will provide the opportunity to test our procedure for reconstructing positions A and B of the skeleton.

The greatest practical disadvantage of this procedure is the large amount of time necessary to create digital replicas of each bone, as well as the lengthy process of 3D animation and simulation. With regards to the former, we strongly recommend creating digital replicas of the bones of the individual under study. While replacing these with digital standard skeletons (e.g. the Motioncow skeleton) would save a considerable amount of time and may be suitable for certain archaeological and forensic purposes (Valente, 2019; Villa, Olsen, & Hansen, 2017), based on our experience reconstructing bone positions using only a few projected 2D images, the specific individual anatomy (size and morphology) is very important in order to reconstruct the position of the bones. Differences in shape between the digital standard skeleton and the individual under study make approximation of the bone position using the standard skeleton very difficult to achieve. While the process of reconstruction and simulation is time consuming, the procedure represents a valuable additional manner to examine human burials with complex taphonomic histories.

This study underscores the fact that the creation of a reconstruction and/or animation is an analytical process in itself, in which the 3D model and/or animation is not necessarily the "end product," but rather a research tool that allows the researcher to closely engage with spatial information. We argue that 3D reconstruction and animation of the taphonomic history of human burials support the archaeothanatological reconstruction process. In our case study, archaeothanatological analysis combined with 3D reconstruction and animation allowed us to better understand and visualize how the ploughing of the landscape would have brought up decomposing human remains, perhaps even of a person known to the individuals operating the plough, and how the remains were (partly) reburied without further disturbing the body. The 3D reconstruction and animation procedure we used strengthens the archaeothanatological analysis, allowing us to envision how the community at Oostwoud-Tuithoorn engaged with the landscape in a way that integrated mortuary ritual and agricultural activities, and adds to the growing number of ways in which 3D visualization can provide a deeper understanding of the human past.

Acknowledgements: This research was supported by the VINNOVA-funded MSCA 'Seal of Excellence' postdoctoral research project. The authors thank the Provinciaal depot voor archeologie Noord-Holland, Castricum, the Netherlands, for providing access to the skeletal remains of Oostwoud-Tuithoorn burial 228, and the authors are very grateful to Joanneke van den Engel-Hees and Martin Veen for their assistance with the 3D documentation.

Author contributions: H.L.M. – conceptualization, investigation, methodology, formal analysis, visualization, funding acquisition, project administration, data curation and writing – original draft preparation. L.N.S. – investigation, formal analysis and writing – review and editing. H.F. – resources, data curation, project administration, writing – review and editing and investigation.

Conflict of interest: Authors state no conflict of interest.

References

Aspöck, E. (2018). A high-resolution approach to the formation processes of a reopened early Bronze Age inhumation grave in Austria: Taphonomy of human remains. *Quaternary International*, *474*, 131–145.

Beacham, R., Denard, H., & Niccolucci, F. (2006). An introduction to the London charter. In D. O. Arnold & M. Iōannidēs (Eds.), *The evolution of information communication technology in cultural heritage: Where Hi-Tech touches the past: Risks and challenges for the 21st century: Papers from the joint event CIPA/VAST/EG/EuroMed 2006, 30. October–4. November 2006, Nicosia, Cyprus*. Budapest: Archaeolingua.

Berggren, Å., Dell'Unto, N., Forte, M., Haddow, S., Hodder, I., Issavi, J., … Taylor, J. (2015). Revisiting reflexive archaeology at Çatalhöyük: Integrating digital and 3D technologies at the trowel's edge. *Antiquity*, *89*, 433–448.

Castex, D., & Blaizot, F. (2017). Reconstructing the original arrangement, organisation and architecture of burials in Archaeology. In E. M. Schotsmans, N. Márquez-Grant, & S. Forbes (Eds.), *Taphonomy of human remains: Forensic analysis of the dead and the depositional environment* (pp. 277–296). Chichester: Wiley.

De Reu, J., Smedt, P. D., Herremans, D., Meirvenne, M. V., Laloo, P., & Clercq, W. D. (2014). On introducing an image-based 3D reconstruction method in archaeological excavation practice. *Journal of Archaeological Science*, *41*, 251–262.

Demetrescu, E. (2015). Archaeological stratigraphy as a formal language for virtual reconstruction. Theory and practice. *Journal of Archaeological Science*, *57*, 42–55.

Demetrescu, E. (2017). Virtual reconstruction as a scientific tool. The extended matrix and source-based modelling approach. In S. Münster, K. Friedrichs, F. Niebling, & A. Seidel-Grzesińska (Eds.), *Digital research and education in architectural heritage. 5th Conference, DECH 2017, and First Workshop, UHDL 2017, Dresden, Germany, March 30–31, 2017, Revised Selected Papers* (pp. 102–116). Cham: Springer.

Demetrescu, E., & Fanini, B. (2017). A white-box framework to oversee archaeological virtual reconstructions in space and time: Methods and tools. *Journal of Archaeological Science: Reports*, *14*, 500–514.

Duday, H. (2006). L'archéothanatologie ou l'archéologie de la mort (Archaeothanatology or the archaeology of death). In R. Gowland & C. Knüsel (Eds.), *Social archaeology of funerary remains*. Oxford: Oxbow Books.

Duday, H. (2009). *The archaeology of the dead: Lectures in archaeothanatology*. Oxford: Oxbow Books.

Duday, H., Courtaud, P., Crubezy, E., Sellier, P., & Tiller, A.-M. (1990). L'anthropologie «de terrain»: Reconnaissance et interprétation des gestes funéraires. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *2*(3–4), 29–49.

Duday, H., & Guillon, M. (2006). Understanding the circumstances of decomposition when the body is skeletonized. In A. Schmitt, E. Cunha, & J. Pinheiro (Eds.), *Forensic anthropology and medicine* (pp. 117–157). Totowa, NJ: Humana Press.

Ferdani, D., Demetrescu, E., Cavalieri, M., Pace, G., & Lenzi, S. (2020). 3D modelling and visualization in field archaeology. From survey to interpretation of the past using digital technologies. *Groma*, *4*, 1–21. doi: 10.12977/groma26.

Fokkens, H. (1998). *Drowned landscape: The occupation of the western part of the Frisian-Drentian Plateau, 4400 BC–AD 500*. Assen: Uitgeverij Van Gorcum.

Fokkens, H., Veselka, B., Bourgeois, Q., Olalde, I., & Reich, D. (2017). Excavations of Late Neolithic arable, burial mounds and a number of well-preserved skeletons at Oostwoud-Tuithoorn: A re-analysis of old data. *Analecta Praehistorica Leidensia*, *47*, 95–150.

Green, E. C. (2018). *What are we missing? An archaeothanatological approach to late Anglo-Saxon burials*. (PhD thesis). University of Sheffield, Sheffield. Retrieved from http://etheses.whiterose.ac.uk/22813/

Haddow, S., Sadvari, J., Knüsel, C., & Hadad, R. (2016). A tale of two platforms: Commingled remains and the life-course of houses at Neolithic Çatalhöyük. In A. Osterholtz (Ed.), *Theoretical approaches to analysis and interpretation of commingled human remains. Bioarchaeology and social theory* (pp. 5–29). Cham: Springer.

Harris, N., & Tayles, N. (2012). Burial containers – A hidden aspect of mortuary practices: Archaeothanatology at Ban Non Wat, Thailand. *Journal of Anthropological Archaeology*, *31*(2), 227–239.

Knüsel, C. (2014). Crouching in fear: Terms of engagement for funerary remains. *Journal of Social Archaeology*, *14*(1), 26–58.

Knüsel, C., Haddow, S., Sadvari, J., Dell'Unto, N., & Forte, M. (2013). Bioarchaeology in 3D: Three-dimensional modeling of human burials at Neolithic Çatalhöyük. *American Journal of Physical Anthropology*, *150*(S56), 170–171.

Maureille, B., & Sellier, P. (1996). Dislocation en ordre paradoxal, momification et décomposition: Observations et hypothèses. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, *8*(3), 313–327.

Mickleburgh, H. L. (2018). Actualistic experimental taphonomy of inhumation burial. In P. M. Barone & W. J. M. Groen (Eds.), *Multidisciplinary approaches to forensic archaeology* (pp. 105–114). Cham: Springer.

Mickleburgh, H. L., & Wescott, D. J. (2018). Controlled experimental observations on joint disarticulation and bone displacement of a human body in an open pit: implications for funerary archaeology. *Journal of Archaeological Science: Reports 20*, 158–167.

Mickleburgh, H. L., Wescott, D. J., Gluschitz, S., & Klinkenberg, M. V. (in press). Exploring the use of actualistic forensic taphonomy in the study of (forensic) archaeological human burials: an actualistic experimental research programme at the Forensic Anthropology Center at Texas State University (FACTS), San Marcos, Texas. In C. Knüsel & E. Schotsmans (Eds.), *Handbook on Archaeothanatology*. London: Routledge.

Nelson, A. J. (1998). Wandering bones: Archaeology, forensic science and Moche burial practices. *International Journal of Osteoarchaeology*, *8*(3), 192–212.

Nilsson Stutz, L. (2003). *Embodied rituals and ritualized bodies: Tracing ritual practices in Late Mesolithic burials*. Stockholm: Almqvist & Wiksell International.

Nilsson Stutz, L. (2006). Unwrapping the dead. Searching for evidence of wrappings in the mortuary practices at Zvejnieki. In L. Larsson & I. Zagorska (Eds.), *Back to the origin. New research in the Mesolithic-Neolithic Zvejnieki cemetery and environment, northern Latvia* (pp. 217–233). Stockholm: Almqvist & Wiksell International.

Olalde, I., Brace, S., Allentoft, ME., Armit, I., Kristiansen, K., Booth, T., … Altena, E. (2018). The Beaker phenomenon and the genomic transformation of northwest Europe. *Nature*, *555*(7695), 190–196.

Ortiz, A., Chambon, P., & Molist, M. (2013). "Funerary bundles" in the PPNB at the archaeological site of Tell Halula (middle Euphrates valley, Syria): Analysis of the taphonomic dynamics of seated bodies. *Journal of Archaeological Science*, *40*(12), 4150–4161.

Peyroteo Stjerna, R. (2016). *On death in the Mesolithic: Or the mortuary practices of the last hunter-gatherers of the South-Western Iberian Peninsula, 7th–6th Millennium BCE*. (PhD thesis). Uppsala University, Uppsala.

Porter, S., Roussel, M., & Soressi, M. (2016). A simple photogrammetry rig for the reliable creation of 3D artifact models in the field: Lithic examples from the Early Upper Paleolithic sequence of Les Cottés (France). *Advances in Archaeological Practice*, *4*(1), 71–86.

Sapirstein, P., & Murray, S. (2017). Establishing best practices for photogrammetric recording during archaeological fieldwork. *Journal of Field Archaeology*, *42*(4), 337–350.

Tõrv, M. (2016). *Persistent Practices. A multi-disciplinary study of hunter-gatherer mortuary remains from c. 6500–2600 cal. BC, Estonia*. (PhD thesis). University of Tartu, Tartu, Estonia.

Ulguim, P. (2017). Chapter 6 – Recording in situ human remains in three dimensions: Applying digital image-based modeling. In T. Thompson & D. Errickson (Eds.), *Human remains: Another dimension: The application of imaging to the study of human remains* (pp. 71–92). London: Academic Press.

Valente, R. (2019). Digital workflow to improve osteoarchaeological osteoarchaeological documentation. *Digital Applications in Archaeology and Cultural Heritage*, *13*, e00097.

Villa, C., Olsen, K. B., & Hansen, S. H. (2017). Virtual animation of victim-specific 3D models obtained from CT scans for forensic reconstructions: Living and dead subjects. *Forensic Science International*, *278*, e27–e33.

Wilhelmson, H., & Dell'Unto, N. (2015). Virtual taphonomy: A new method integrating excavation and postprocessing in an archaeological context. *American Journal of Physical Anthropology*, *157*, 305–321.

Willis, A., & Tayles, N. (2009). Field anthropology: Application to burial contexts in prehistoric Southeast Asia. *Journal of Archaeological Science*, *36*(2), 547–554.